

# **Pulsed High Temperature Superconducting Central Solenoid For Revolutionizing Tokamaks**

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# Team members and roles



## Management



Bob Mumgaard, CEO  
and DOE PI



Brandon Sorbom  
VP R&D / CSO

## Supply Chain



Moses Bloom,  
Senior Buyer



Nathan Hirsch,  
Senior Buyer

## Legal & Finance



Michael Segal,  
Head of Open Innovation



Shamika Naidu,  
Grants Administrator

## Technical Team



Elle Allen,  
Project Manager



Erica Salazar, Quench  
Technical Lead



Owen Duke, Quench  
Research Scientist



Chris Craighill,  
Analyst



Charlie Sanabria,  
Magnet Engineer



Sam Heller,  
Manufacturing  
Design Engineer



Justin Carmichael,  
Sr. Mech. Engineer



Alex Warner,  
Lead Manufacturing  
Engineer



David Mendoza,  
Lead Manufacturing  
Equipment Engineer



Julio Colque,  
Magnet Engineer



Kristen Metcalfe,  
Controls Engineer

# Key Terminologies



## SPARC

- A compact, high-field tokamak that will pave the way for CFS to produce plasmas which generate more energy than they consume.

## ARC

- Designed as a fusion power plant, ARC will produce fusion power onto the grid and demonstrate the science and technology required for economically competitive, mass production of fusion power.

## HTS

- High-Temperature Superconductor

## VIPER

- The first-generation design of an industrially scalable high-current high-temperature superconductor cable

## PIT VIPER

- The next-generation design of VIPER with the goal of reducing AC losses by >10x, enabling robust HTS cable in a high dB/dt environment

# High-level motivation, innovation, and goals of the project



## Program Objective and Goal

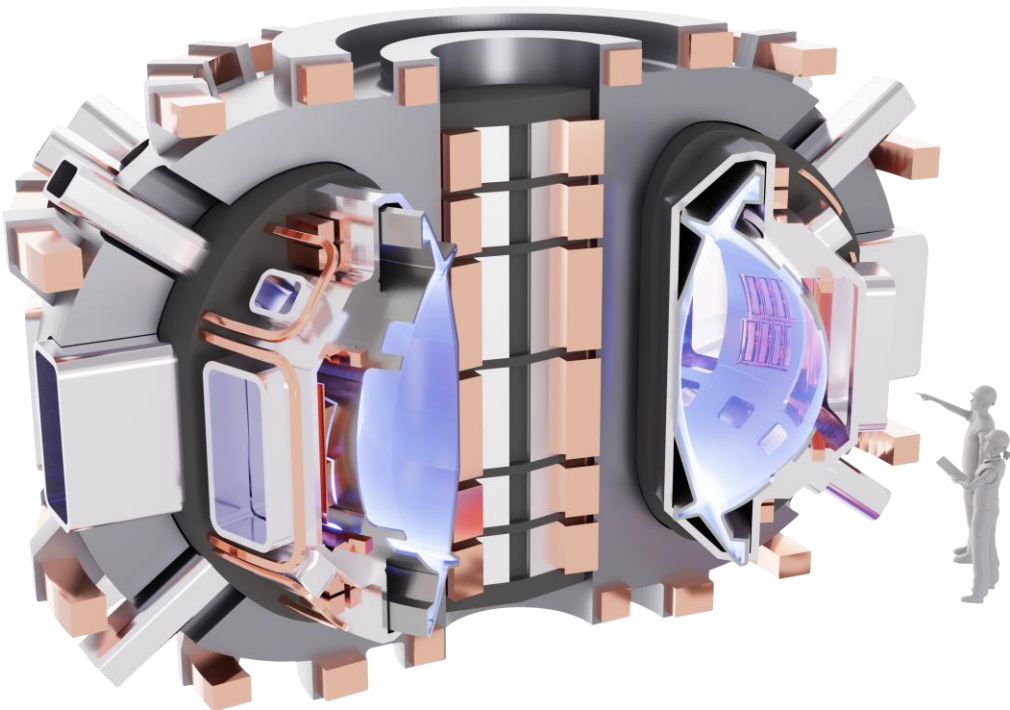
- Design, build and test a pulsed HTS Central Solenoid Model Coil (CSMC) that will retire all significant technical risks of a full-scale fast-ramping high-flux HTS CS for tokamak net-energy demonstrators and power plants

## Motivation

- LTS CS current density & B-field are too low to drive plasma current in an economically viable device.
- This forces power plant tokamaks to be steady state, have expensive external current drives, and use risky physics

## Key Innovations

- Design an HTS cable that can perform to requirements in rapidly changing magnetic fields
- Validate performance requirements of critical subsystems against SPARC operational models
- Develop a manufacturing facility that will allow the construction of a CSMC to test and engineering design specifications



*The CS system, shown in orange above, is the pulsed HTS heart of the SPARC tokamak*

Metric	State of the Art	Proposed CS
Coil Peak Field	10 T	20 T
Coil Ramp Rate	0.4 T/s	4 T/s
Coil Current Density	20 A/mm <sup>2</sup>	85 A/mm <sup>2</sup>

# Major tasks, milestones, risks, and desired project outcomes



## Low-loss Superconducting Cable and Joints

- Validate >10x AC Loss Reduction
- Prove low degradation in SPARC IxB Load Cycling
- Develop Low Resistance HTS Joints
- Demonstrate nominal survivability in structural load and fatigue testing
- Test critical current performance under SPARC structural load cases

## Quench Detection

- Integrate fiber-optic quench detection in PIT VIPER and develop detection algorithm mapping software
- Register temperature rise such that no section of the PIT-VIPER cable is hotter than 150K after a shutdown trigger is executed

## Manufacturing

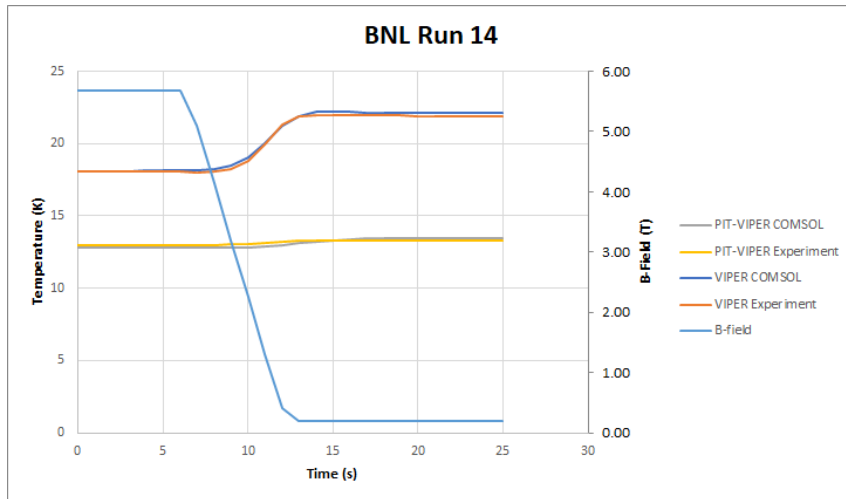
- Design and commission automated former extrusion, tape insertion, jacketing and winding processes
- Fortify feed and sensor systems for quench detection, pulsed power, cryogenics, insulation, and low loss joints

## Validation

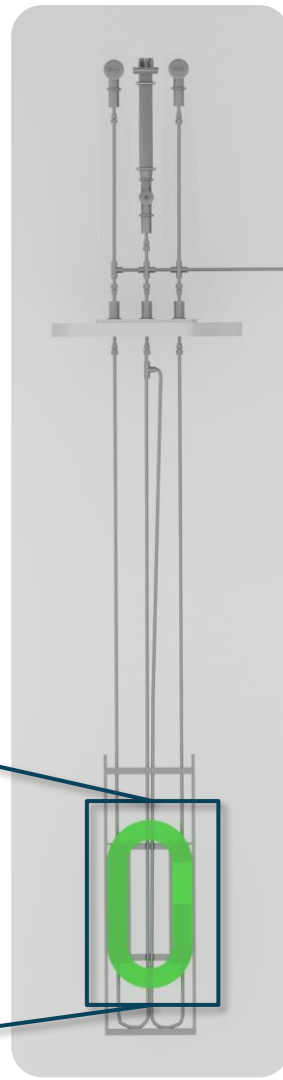
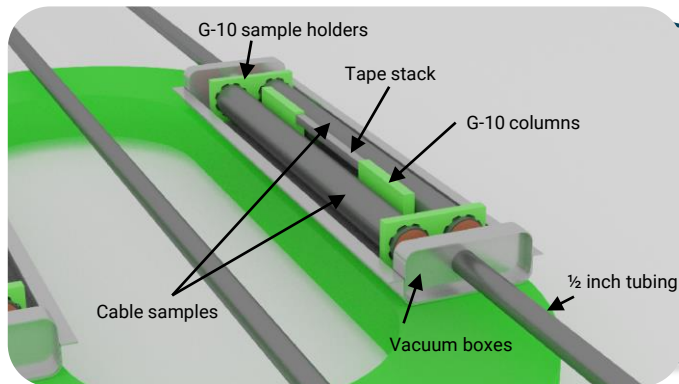
- Test a full coiled layer in a cryogenic test stand designed for high-field, high-ramp testing at ~50 kA and 20 Kelvin to validate models and performance and test quench detection and dump rates.



# Key Performance: AC Loss Reduction for HTS Conductor



*PIT-VIPER experimental heating - matches models and meets SPARC performance demands*



## Goals

- Validate 20-fold AC loss heating reduction from COMSOL models of PIT VIPER cable compared to VIPER cable in representative operational conditions

## Research questions

- Do the modeled projections of AC loss heating differences match in-situ measurements at high field and ramp rates within 30%?
- Can the co-wound quench detection system meet sensing and timing requirements?

## Results

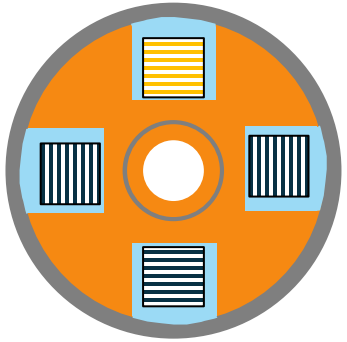
- VIPER and PIT VIPER cables were instrumented and tested in a high field and ramp rate-achievable magnet at Brookhaven National Laboratory
- Calorimetry analyses were done to evaluate AC loss heating along the lengths of the samples, comparing the old and new designs
- Experiments were successful in confirming a 20-fold lower AC loss heating for PIT VIPER than VIPER
- Models matched experimental data within nominal %

Status: Complete

# Key Performance: IxB and Quench Testing at SULTAN

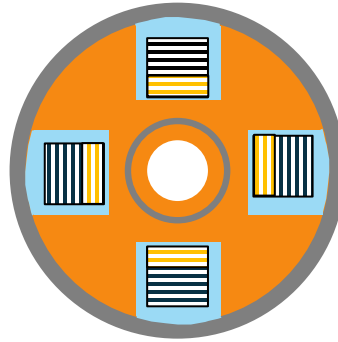


Cable 1 “Diamondback”



(Left)  
Full HTS stack – testing  $I_c$   
degradation

Cable 2 “Egg-Eater”



(Right)  
Split HTS stack – quench  
propagation



Sample installation at SULTAN



## Goals

- Test PIT VIPER cables to representative IxB loading to quantify  $I_c$  degradation through cyclic fatigue loading
- Quench detection/propagation dynamic data collection in-situ

## Research questions

- Do design changes from VIPER to PIT VIPER affect the IxB and structural loading tolerance at the stack level?
- Can we detect a temperature rise indicative of a quench onset sufficiently fast to prevent a jacket surface temperature of 150 K

## Results

- IxB loading after 2000 cycles caused negligibly discernible  $I_c$  degradation
- Valuable quench detection data collected at 4-10K range in  $\sim\Delta 0.5K$  granular increments in large dT/dt events
- In-situ environmental testing complete and shows no degradation to PIT VIPER hardware under IxB fatigue cycling
- Lessons learned translatable to SPARC around successful management and handling of instrumentation

Status: Complete

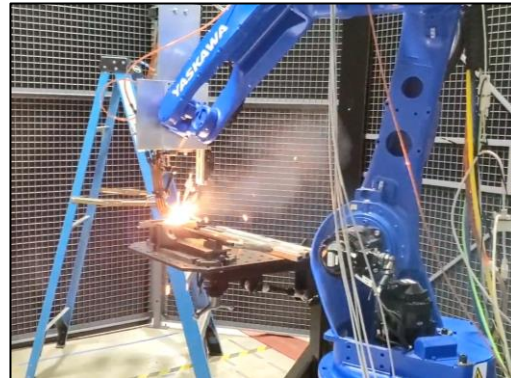
# Automated Manufacturing for Long-Length HTS Conductor



*Recent achievement - making 100+ meter PIT VIPER cable*



*(Above)  
Previous manual build process*



*Automated qualification testing for jacketing processes*

## Goals

- Design and validate reliable manufacturing processes to enable production of PIT VIPER coil magnets at SPARC scale
- Retire as-built risk through extensive process qualification and testing

## Research questions

- Will the cabling line as designed produce PIT VIPER conductor within nominal tolerances?
- Does any manufacturing process operation hold risk of reducing cable performance? What steps can be taken to minimize this?

## Results

- Automated PIT VIPER cabling line designed, sourced, manufactured, installed and commissioned at CFS MFG facility
- 100+ m PIT VIPER cable produced as major milestone with ARPA-E program
- Qualification testing for jacketing process approach is nearly completed, leading to a clearly defined process
- Coil/winding pack manufacturing SOP development is at ~40%

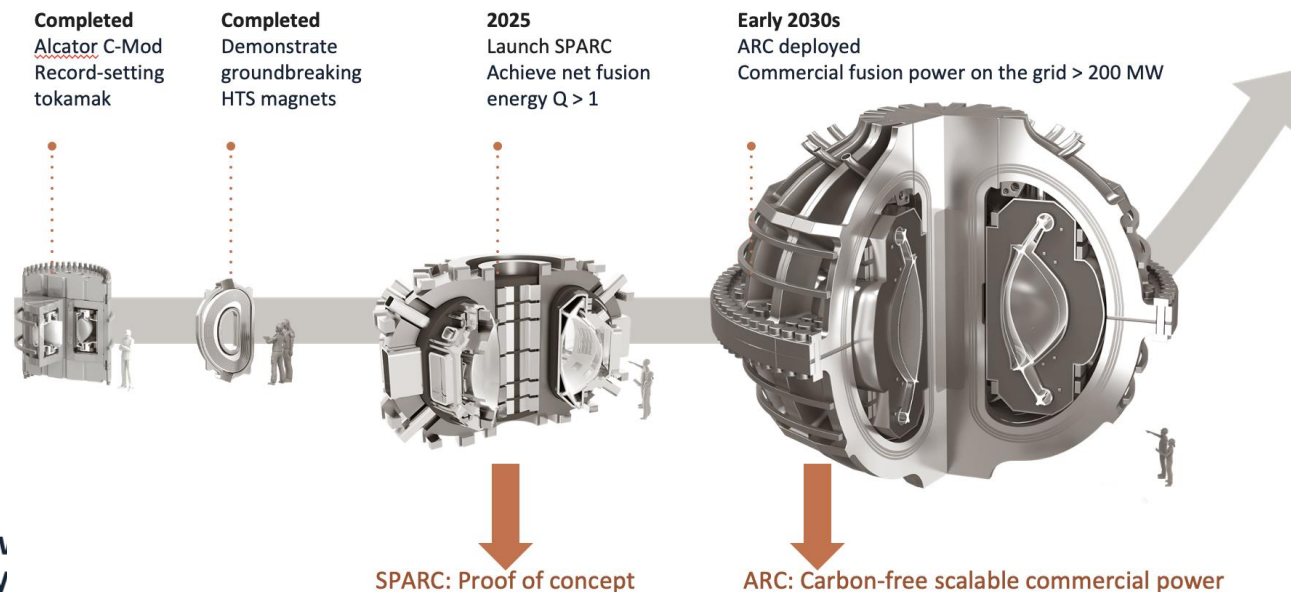
Status: In Progress



# T2M and aspirational follow-on plans



- ▶ Steady-state tokamaks carry physics risk because they require high beta, require expensive external current drive
- ▶ A fast-ramping HTS Central Solenoid reduces physics risk and cost – *no current drive needed*
- ▶ Anticipated improvement in overnight and electricity cost of ~25%-50%
- ▶ CFS is on target to commission SPARC break-even tokamak in 2025
- ▶ SPARC will deploy pulsed Central Solenoid, de-risk its use for ARC commercial device
- ▶ ARC on target for commercial deployment in early 2030's



# Techno-economic metrics and impact: Simple tokamaks



- HTS importance and impact

- Optimizing for pulsed operation with LTS CS leads to very large, low power density machines, driving up \$/W
  - Magnitude of impact seen right, comparing:
  - EU-DEMO - existing plasma physics, LTS magnets
  - AIRES AT and RS - enhanced confinement, current drive, LTS
  - HTS TF and plasma physics improvements
  - Original ARC study which assumes an HTS TF, LTS CS, and Lower Hybrid Current Drive (LHCD)
  - HTS TF and HTS CS with no plasma physics improvements
- Clear trade between engineering complexity and physics complexity – innovations in industrial HTS magnets can now be used to simplify tokamaks

